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Search for first generation scalar leptoquarks

The CDF Collaboration
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We report on the search for pair production of scalar leptoquarks using ~ 200 pb^{-1} of proton-antiproton collision data recorded by the CDF experiment during Run II of the TeVatron.

Leptoquarks are assumed to be pair produced and to decay into a charged lepton and a quark of the same generation with branching fraction β. Cases where (i) both leptoquarks decay into and electron and a quark and (ii) one leptoquark decays into and electron and a quark while the other goes to a neutrino and a quark are considered. We observed no evidence for leptoquark production and set an upper cross section limit of 0.09 pb ($\beta = 1$) at 95% C.L. for the $eejj$ and 0.29 pb ($\beta = 0.5$) at the 95% C.L. for the $e\nu\,jj$ channels.

These limits translate into 95% C.L. upper limits on the scalar leptoqaurk mass, of, respectively, 230 GeV/c^2 ($\beta = 1$) and 176 GeV/c^2 ($\beta = 0.5$).

Preliminary Results for Summer 2004 Conferences

I. INTRODUCTION

A common feature of theoretical models trying to imagine possible scenarios for new physics is the symmetry between quarks and leptons suggested by the Standard Model, and the search for a more foundamental relation between them. Theories like Grand Unification and R-parity violating Supersymmetry introduce the idea of quark to lepton transitions, therefore suggesting that particles carrying both lepton and baryon number exist. Among the rich fauna of exotic particles, leptoquarks are of special interest as they could be the mediator of this new kind of lepton-quark interaction.

Leptoquarks are hypothetical color-triplet particles carrying both baryon and lepton quantum numbers and are predicted by many extension of the Standard Model as new bosons coupling to a lepton-quark pair. Their masses are not predicted. They can be scalar particles (spin 0) or vector (spin 1) and at high energy hadron colliders they would be produced directly in pairs, mainly through gluon fusion or quark antiquarks annihilation. The couplings of the leptoquarks to the gauge sector are predicted due to the gauge symmetries, up to eventual anomalous coupling in the case of vector leptoquarks, whereas the fermionic couplings are free parameters of the models. In most models leptoquarks are expected to couple only to fermions of the same generations because of experimental constraints as non observation of flavor changing neutral currents or helicity suppressed decays. At the TeVatron leptoquarks would be pair produced and would decay into a lepton and quark of the same generation. Traditionally the branching ratio describing the decay of the leptoquark into a charge lepton and and quark is called β. The cross section for the pair production of scalar leptoquarks in $p\bar{p}$ has been calculated to next-to-leading order (NLO) in perturbative QCD[1].

We report on a search for scalar leptoquarks in the di-electrons and jets topology and electron, missing transverse energy and jets topology, sensitive respectively to $\beta = 1$ and $\beta = 0.5$, using ~ 200 pb^{-1} of $p\bar{p}$ collisions data at a center of mass energy of 1.96 TeV recorded by the Collider Detector at Fermilab (CDF) during the 2002-2003 TeVatron Run II. Previous limits on leptoquarks production from TeVatron Run I, HERA and LEP are summarized in [2].

CDF is a general purpose detector and is described in detail in [3]. A short description of its main components is briefly outlined here. Closest to the beam pipe is the charged particle tracking system used to reconstruct particle momenta and the collision vertex. It consists of a multi-layer silicon detectors and a large open-cell drift chamber covering the pseudorapidity region $|\eta| \leq 1$. The tracking system is enclosed in a superconducting solenoid. It is surrounded by a calorimeter, organized into electromagentic and hadronic sections segemented into projective tower geometry covering the $|\eta| \leq 3.6$ region. The central and plug electromagnetic calorimeters utilize a lead scintillator sampling technique, whereas the central, wall and plug hadron calorimeter use iron-scintillator technology. Outside the central calorimeter there is a muon detection system, which covers the range $|\eta| \leq 2$.

II. THE 2 ELECTRONS AND 2 JETS CHANNEL

A. Data Sample & Event Selection

This analysis is based on an integrated luminosity of 203 pb^{-1} collected with the CDFII detector between March 2002 and September 2003. The data are collected with an inclusive lepton trigger that requires an electron with E_T >18 GeV (and several stringent identification cuts on the electromagnetic cluster and track) or E_T >70 GeV (and slightly less stringent identification cuts on the electromagentic cluster).

From this inclusive lepton dataset we select events offline with two reconstructed isolated electrons with E_T greater than 25 GeV. The first electron is required to be central ($|\eta| \leq 1$, we will call is C electron), while the second can be central or plug ($1 \leq |\eta| \leq 3$, we will call it P electron). Events are further selected if there are at least two jets with E_T >30 GeV in the range $|\eta| \leq 2$. The dataset selected above is dominated by QCD production of Z bosons in association with jets and top quark (where both the W's from top decay go into an electron and neutrino). To reduce this background, while at the same time maintain a reasonable efficiency for detecting the LQ signal the following cuts are applied:

- Removal of events with $76 < M_{ee} < 110$ GeV/c^2;
- $E_T(j_1) + E_T(j_2) > 85$ GeV AND $E_T(e_1) + E_T(e_2) > 85$ GeV;
- $\sqrt{((E_T(j_1) + E_T(j_2))^2 + (E_T(e_1) + E_T(e_2))^2)} > 200$ GeV

B. Total Signal Acceptance

The efficiency for detecting leptoquarks decaying into electrons and quarks is the product of several factors:

$$\epsilon_{total} = A(M) \times \epsilon_{id} \times \epsilon_{trigger} \times \epsilon_{vertex}$$

where A(M) is the product of the kinematical and geometrical acceptance, obtained from MC simulated LQ data (the PYTHIA Monte Carlo program [4] was used), ϵ_{id} is the identification efficiency for 2 electrons, obtained from Z data ($\epsilon_{CC} = 0.924 \pm 0.004$, $\epsilon_{CP} = 0.792 \pm 0.005$), $\epsilon_{trigger}$ is the trigger efficiency ($\epsilon_{trigger} = 0.991 \pm 001$) and ϵ_{vertex} is the efficiency for the event vertex cut, also obtained from data ($\epsilon_{vertex} = 0.952 \pm 001(stat) \pm 005(sys)$).

The final signal efficiency is reported in Figure 1.

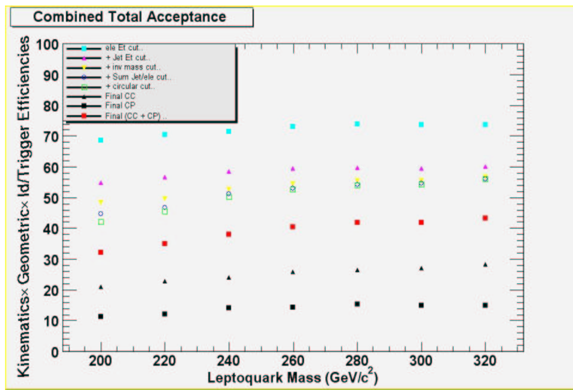

FIG. 1: Signal efficiency as function of the leptoquark mass, *ee jj* analysis

C. Backgrounds

The main SM processes representing irreducible background to the Leptoquark production process are due to $\gamma/Z \rightarrow ee$ events accompanied by jets due to radiation. The main component of this background is eliminated by cuts on M_{ee} around the mass of the Z boson and the ΣE_T cuts. However there are still events from the DY continuum and Z events that fail the cuts due to mis-measurement. We studied the distribution of this background by generating the process Z + 2 jets with Alpgen[6] and using the MC parton generator mcfm[5] to obtain the NLO cross section. Another source of background is represented by $t\bar{t}$ production where both the W decay into $e\nu$. Other backgrounds from $b\bar{b}$, $Z \rightarrow \tau\bar{\tau}$, WW are expected to be negligible due to the electron isolation and large electron and jet transverse energy requirements. The expected number of DY + 2 jets events in 203.2 pb-1 is 1.89 ± 0.44. The expected number of $t\bar{t}$ events is 0.35 ± 0.03 events. To normalize simulated events to data we used the theoretical cross section for $t\bar{t}$, $\sigma(t\bar{t}) \times Br(W \rightarrow e\nu)$, and the theoretical cross section for $\gamma\ Z \rightarrow ee$ + 2 jets obtained with mcfm. The total number of expected background events is 2.24 +/- 0.55.

Another irreducible source of background is represented by events where a jet is mismeasured as an electron (fakes). We used 2 methods to estimate the fakes background. The first is the isolation method, the second is the one based on the counting of same sign events to estimate the contamination from dijets faking electrons (this last method is only valid for central-central electrons, as we don't use tracking information for plug electrons).

The isolation method relies on the assumption that since jets are produced in association with other particles, the isolation fraction of a jet will be generally larger than the one corresponding to an electron. The phase space corresponding to the 2 electrons isolation fractions is divided in 4 regions: For central-central :

- Region A) $Iso_1 < 0.1$, $Iso_2 < 0.2$;
- Region B) $Iso_1 < 0.1$, $0.2 < Iso_2 < 0.4$;
- Region C) $0.2 < Iso_1 < 0.4$, $Iso_2 < 0.2$;
- Region D) $0.2 < Iso_1 < 0.4$, $0.2 < Iso_2 < 0.4$;

For central-plug:

- Region A) $Iso_1 < 0.1$, $Iso_2 < 0.1$;
- Region B) $Iso_1 < 0.1$, $0.2 < Iso_2 < 0.4$;
- Region C) $0.2 < Iso_1 < 0.4$, $Iso_2 < 0.1$;
- Region D) $0.2 < Iso_1 < 0.4$, $0.2 < Iso_2 < 0.4$;

The following assumptions are made: there is no correlation between the isolation of the 2 electrons, signal events are only in region A, all events in the other regions being background events. If we assume that the ratio of A to B equals the ratio of C to D for QCD events, we can estimate how many QCD events we will have in the A region.

The second method counts the number of same sign events. The assumption is made that the probability of negative charge found in the highest P_T track in a jet is roughly the same as for positive charge.

After comparing the 2 methods we estimate $0^{+0.7}_{-0}$ fake events in the Central-Central category and 3.96 ± 1.98 in the Central-Plug category. The final background estimate is : 6.24 ± 3.5.

D. Systematic uncertainty

The following systematic uncertainty is considered:

- Luminosity: 6%
- Acceptance:
  - pdf 4.3%
  - statistical error of MC 2.2%
  - Jet energy scale < 1%
- Electron ID efficiency
  - statistical error of $Z \rightarrow e^+e^-$ sample: 0.8%
- Event vertex cut : 0.5%

Adding the above systematic uncertainty in quadrature will give a total systematic uncertainty of about 8.5%. The total relative uncertainty on the acceptances varies from 13% to about 8%, decreasing monotonically with the increase in the LQ mass. Final signal efficiencies and uncertainties are reported in table below.

M(LQ) GeV/c^2	Acceptance (%)	Abs Stat	Abs Sys	Relative total Uncertainty
200	32.24	0.85	4.57	0.14
220	35.07	0.79	4.13	0.12
240	38.11	0.80	3.8	0.10
260	40.4	0.82	3.7	0.09
280	41.8	0.84	3.6	0.087
300	41.9	0.84	3.5	0.084
320	43.3	0.84	3.4	0.080

TABLE I: Final Signal Efficiency and Errors.

E. Results

After all selection cuts, 4 events are left.

The production cross section s of the process $LQLQ \rightarrow eejj$ can be written as follows:

$$\sigma \times Br(LQLQ \rightarrow eejj) = \sigma \times \beta^2 = \frac{N}{(\epsilon \times L)},$$

where N is the number of observed events on data after our selection, ϵ is the total selection efficiency as a function of M(LQ) and it L is the integrated luminosity. As we found 4 candidate events in our selection, we set a 95% C.L. upper limit on the cross section as a function of M(LQ) defined as:

$$\sigma_{lim} = \frac{N_{lim}}{(e \times L \times \beta^2)}$$

In Figure 2 the limit cross-section as function of M(LQ) is compared with the theoretical expectations for $\beta = 1$. At the intersection point between experimental and theoretical curves we find the lower limit on M(LQ) at 230 GeV/c^2.

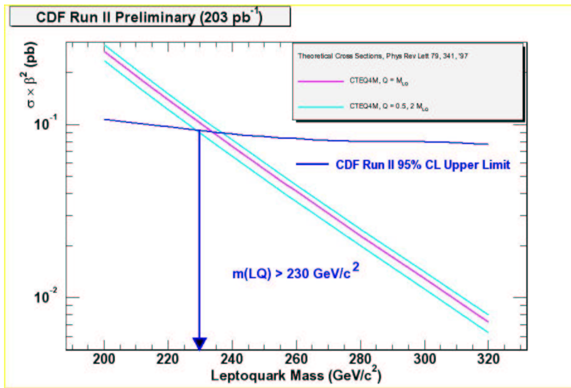

FIG. 2: Limit cross section as a function of M(LQ) compared with the theoretical expectations calculated at NLO accuracy. At the intersection points between experimental and theoretical curves we find a lower limit on M(LQ) at 230 GeV/c^2 for $\beta = 1$.

III. THE ELECTRON, NEUTRINO AND 2 JETS CHANNEL

A. Data Sample & Event Selection

This analysis is based on an integrated luminosity of 203 pb^{-1} collected with the CDFII detector between March 2002 and September 2003. The data are collected with an inclusive lepton trigger that requires an electron with E_T >18 GeV (and several stringent identification cuts on the electromagnetic cluster and track) or E_T >70 GeV (and slightly less stringent identification cuts on the electromagentic cluster).

From this inclusive lepton dataset we select events offline with one reconstructed isolated electrons with E_T greater than 25 GeV. The electron is required to be central ($|\eta| \leq 1$). We veto events with a second central or plug electron (to be orthogonal to the previous analysis). We then select events where there is large missing transverse energy, $\not{E}_T > 60$ GeV and at least two jets with E_T >30 GeV in the range $|\eta| \leq 2$. The dataset selected above is dominated by QCD production of W bosons in association with jets and top quark (decaying inot dilepton and lepton + jets mode). To reduce this background, while at the same time maintaining a reasonable efficiency for detecting the LQ signal the following cuts are applied:

- $\Delta\Phi(MET - jet) > 10^o$ to veto events where the transverse missing energy is mismeasured due to a mismeasured jet;
- $E_T(j_1) + E_T(j_2) > 80GeV$
- $M_T(e\nu) > 120GeV/c^2$ to reduce the W + 2 jets background.

Finally we select events falling in mass windows defined around the nominal LQ masses. This cut allows us to better discriminate background from signal as the data (assumed to be composed of background only) will lay in a random way in respect to the preferential position of signal around the LQ mass.

To select leptoquark candidates of a given mass we built the invariant mass of the electron-jet system and the transverse mass of the neutrino-jet system. Given the decay of the two LQs, there are two possible mass combinations for the electron and the neutrino with the 2 leading jets. We choose the masses that minimize the difference between the electron-jet mass and the neutrino-jet transverse mass. We fitted the peak of the *e-jet* distribution with a Gaussian, to obtain a rough estimate of the spread of the distribution in the signal region. We did this exercise for several LQ masses and concluded that the spread σ_e is on average 15% (increasing with the LQ mass). We then operate a $3\sigma_e$ cut around the nominal leptoquark mass to select leptoquark candidates of a given mass. The $\nu - jet$ transverse mass distribution is also fitted with a Gaussian, taking into account its high tail. The spread σ_ν is thus found tipically to be on average 25% of the leptoquark mass (increasing with the LQ mass). In the end, those 3σ mass cuts can be represented by boxes in the 2-dimensional plane defined by the invariant mass $e - jet$ and the transverse mass $\nu - jet$.

B. Total Signal Acceptance

The efficiency for detecting leptoquarks decaying into electron/neutrino and quarks is the product of several factors:

$$\epsilon_{total} = A(M) \times \epsilon_{id} \times \epsilon_{trigger} \times \epsilon_{vertex}$$

where A(M) is the product of the kinematical and geometrical acceptance, obtained from MC simulated LQ data (the PYTHIA Monte Carlo program [4] was used), ϵ_{id} is the identification efficiency for 1 central electron, obtained from Z data ($\epsilon_C = 0.962 \pm 0.004$), $\epsilon_{trigger}$ is the trigger efficiency (0.96 ± 001) and ϵ_{vertex} is the efficiency for the event vertex cut, also obtained from data ($0.952 \pm 001(stat) \pm 005(sys)$). Kinematical and geometrical efficiencies are multiplied by the scale factor between data and simulation. The final signal efficiency is reported in Figure 3.

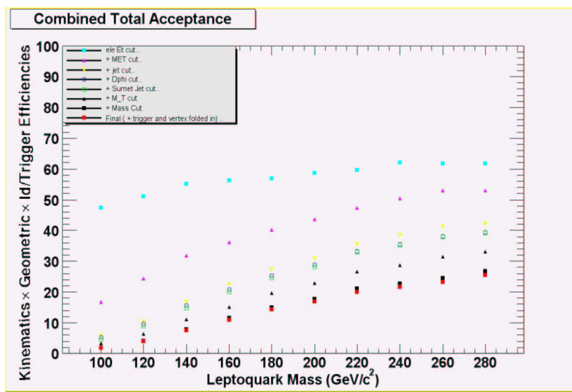

FIG. 3: Signal efficiency as function of the leptoquark mass, $e\nu\ jj$

C. Backgrounds

The main SM processes contrbuting to the irreducible background to the LQ signal, is due to $W \to e\nu$ events accompanied by jets due to radiation. The main component of this background is eliminated by cuts on M_T of the electron and neutrino. We studied the distribution of this background by generating the process W + 2 jets with Alpgen[6] and using the MC parton generator mcfm[5] to obtain the NLO cross section. Another source of background is represented by $t\bar{t}$ production where both the W decay into $e\nu$ and one lepton is mismeasured or one of the W decay leptonically and the other hadronically (lepton + jets). A small source of background is represented by Z + 2 jets, where one of the electrons is misidentified . This process have been generated with Alpgen. The background from $W \to \nu\tau$ + 2 jets is negligible after the final window mass cut. To normalize simulated events to data we used the central value of the theoretical cross section for $t\bar{t}$, $\sigma(t\bar{t}) = 6.7$ pb , and the theoretical cross section for W + 2 jets and Z + 2 jets from mcfm (294 pb for $W + 2jets \times Br(W \to l\nu)$ and 98pb for $Z + 2jets \times Br(Z \to ll)$).
The QCD fakes background is negligible.

D. Systematic uncertainty

The following systematic uncertainty is considered:

- Luminosity: 6%

- Acceptances
  - pdf 2.1%
  - statistical error of MC 2.2%
  - Jet energy scale ¡ 1%
  - ID scale factor 0.06%
- Event vertex cut : 0.5%
- ISR/FSR 1.7%

Final signal efficiencies and uncertainties are reported in table below.

M(LQ) GeV/c^2	Acceptance (%)	Abs Stat	Abs Sys	Relative total Uncertainty
100	1.7	0.19	0.1	0.135
120	3.8	0.3	0.3	0.104
140	8.5	0.4	0.6	0.09
160	10.7	0.5	0.8	0.086
180	13.9	0.5	1.0	0.082
200	16.5	0.5	1.2	0.082
220	19.5	0.6	1.4	0.080
240	21.0	0.6	1.6	0.080
260	22.6	0.6	1.7	0.079
280	24.9	0.6	1.8	0.078

TABLE II: Final Signal Efficiency and Errors.

E. Results

The number of events surviving in each mass region, compared with the background expectations are reorted in table III.

M(LQ) GeV/c^2	120	140	160	180	200	220	240	260	280
W + 2 jets	1.5 ± 0.9	1.5 ± 0.9	2.5 ± 1.13	2.5 ± 1.13	2.5 ± 1.13	2.0 ± 1.0	2.0 ± 1.0	1.5 ± 0.8	0.5 ± 0.4
top	3.08 ± 0.6	2.9 ± 0.6	2.6 ± 0.6	2.3 ± 0.5	1.8 ± 0.5	1.5 ± 0.3	1.0 ± 0.3	0.7 ± 0.2	0.6 ± 0.2
Z + 2 jets	0.05 ± 0.01	0.08 ± 0.02	0.08 ± 0.02	0.08 ± 0.02	0.08 ± 0.02	0.06 ± 0.02	0.06 ± 0.02	0.04 ± 0.01	0.04 ± 0.01
Total	4.7 ± 4.3	4.5 ± 4.0	5.16 ± 4.3	4.85 ± 4.0	4.5 ± 3.8	3.6 ± 3.2	3.1 ± 2.8	2.3 ± 2.1	1.1 ± 1.0
Data	6	4	4	4	4	2	2	2	1

TABLE III: Final number of events surviving all cuts, compared with background expectations

As before, the production cross section s of the process $LQLQ \to e\nu jj$ can be written as follows:

$$\sigma \times Br(LQLQ \to e\nu jj) = \sigma \times 2\beta(1-\beta) = \frac{N}{(\epsilon \times L)},$$

where N is the number of observed events on data after our selection, ϵ is the total selection efficiency as a function of M(LQ) and it L is the integrated luminosity. Given the number of survuving events, we set a 95% C.L. upper limit on the cross section as a function of M(LQ) defined as:

$$\sigma_{lim} = \frac{N_{lim}}{(e \times L \times 2\beta(1-\beta))}$$

In Figure 4 the limit cross-section as function of M(LQ) is compared with the theoretical expectations for $\beta = 0.5$. At the intersection point between experimental and theoretical curves we find the lower limit on M(LQ) at 176 GeV/c^2.

In Figure 5 and 6 the final invariant *e-jet* mass distribution and transverse mass distribution ν *-jet* corresponding to the minimum difference between the two, and before the individual LQ's mass window cut is plotted. Data are compared to hypothetical signal for m(LQ) = 200 GeV/c^2.

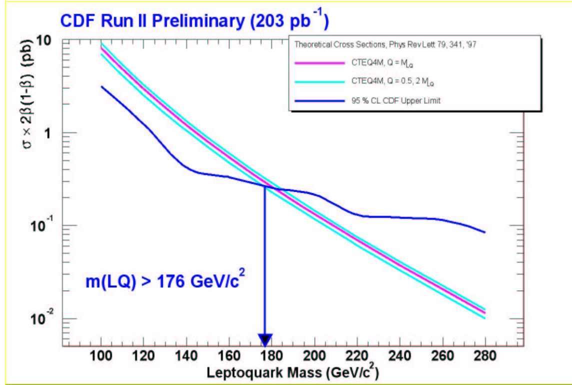

FIG. 4: Limit cross section as a function of M(LQ) compared with the theoretical expectations calculated at NLO accuracy. At the intersection points between experimental and theoretical curves we find a lower limit on M(LQ) at 176 GeV/c^2 for $\beta = 0.5$.

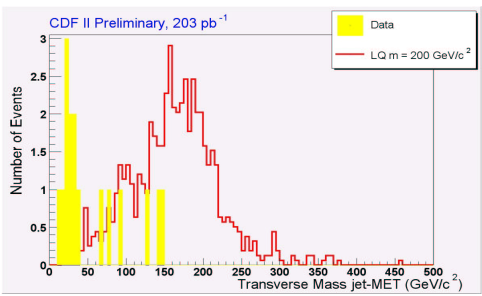

FIG. 5: Transverse mass distributions of the neutrino-jet picked up by the mass cut algorithm. The data include all the events (for all mass window). In red its the distribution of LQ signal for m(LQ) = 200 GeV/c^2.

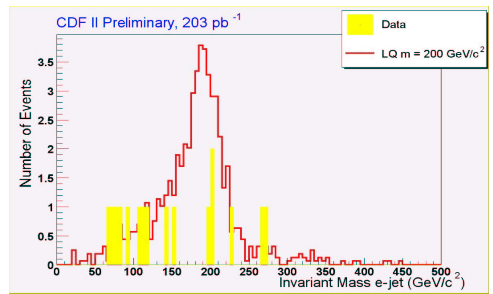

FIG. 6: Invariant mass distributions of the electron-jet picked up by the mass cut algorithm. The data include all the events (for all mass window). In red its the distribution of LQ signal for m(LQ) = 200 GeV/c^2.

IV. CONCLUSIONS

We have reported on the search for pair production of scalar leptoquarks using ~ 200 pb^{-1} of proton-antiproton collision data recorded by the CDF experiment during Run II of the TeVatron.

Leptoquarks are assumed to be pair produced and to decay into a charged lepton and a quark of the same generation with branching fraction β. Cases where (i) both leptoquarks decay into and electron and a quark and (ii) one leptoquark decays into and electron and a quark while the other goes to a neutrino and a quark are considered. We observed no evidence for leptoquark production and set an upper cross section limit of 0.09 pb ($\beta = 1$) at 95% C.L. for the $eejj$ and 0.29 pb ($\beta = 0.5$) at the 95% C.L. for the $e\nu\ jj$ channels.

These limits translate into 95% C.L. upper limits on the scalar leptoqaurk mass, of, respectively, 230 GeV/c^2 ($\beta = 1$) and 176 GeV/c^2 ($\beta = 0.5$).

Acknowledgments

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Research; the Comision Interministerial de Ciencia y Tecnologia, Spain; and in part by the European Community's Human Potential Programme under contract HPRN-CT-20002, Probe for New Physics.

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